DUAL BAND COPLANAR MICROSTRIP INTERLACED ARRAY

CROSS REFERENCE TO RELATED APPLICATION

This application is a divisional application of U.S. Patent Application Serial No. 10/056,413, filed January 24, 2002, now U.S. Patent No. _________, the entire disclosure of which is hereby incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates to dual band, coplanar antennas. In particular, the present invention relates to dual band coplanar antennas having interlaced arrays to minimize the surface area required by the antenna.

BACKGROUND OF THE INVENTION

Antennas are used to radiate and receive radio frequency signals. The transmission and reception of radio frequency signals is useful in a broad range of activities. For instance, radio wave communication systems are desirable where communications are transmitted over large distances. In addition, radio frequency signals can be used in connection with obtaining geographic position information.

In order to provide desired gain and directional characteristics, the dimensions and geometry of an antenna are typically such that the antenna is useful only within a relatively narrow band of frequencies. It is often desirable to provide an antenna capable of operating at more than one range of frequencies. However, such broadband antennas typically have less desirable gain characteristics than antennas that are designed solely for use at a narrow band of frequencies. Therefore, in order to provide acceptable gain at a variety of frequency bands, devices have been provided with multiple antennas.

Although such an approach is capable of providing high gain at multiple frequencies, the provision of multiple antennas requires relatively large amounts of physical space.

An example of a device in which relatively high levels of gain at multiple frequencies and a small antenna area are desirable are wireless telephones capable of operating in connection with different wireless communication technologies. In particular, it may be desirable to provide a wireless telephone capable of operating in connection with different wireless systems having different frequencies, when communication using a preferred system is not available. Furthermore, in wireless telephones, a typical requirement is that the telephone provide high gain, in order to allow the physical size and power consumption requirements of the telephone components to be small.

Another example of a device in which high gain characteristics at multiple frequencies and a small antenna area are desirable are global positioning system (GPS) receivers. In particular, GPS receivers using dual frequency technologies, or using differential GPS techniques, must be capable of receiving weak signals transmitted on two different carrier signals. As in the example of wireless telephones, it is generally desirable to provide GPS receivers that are physically small, and that have relatively low power consumption requirements.

Still another example of a device in which a relatively high gain at multiple frequency bands is desirable is in connection with a communications satellite or a global positioning system satellite. In such applications, it can be advantageous to provide phased array antennas capable of providing multiple operating frequencies and of

directing their beam towards a particular area of the Earth. In addition, it can be advantageous to provide such capabilities in a minimal area, to avoid the need for large and complex radiator structures.

Planar microstrip antennas have been utilized in connection with various devices. However, providing multiple frequency capabilities typically requires that the area devoted to the antenna double (i.e., two separate antennas must be provided) as compared to a single frequency antenna. Alternatively, microstrip antenna elements optimized for operation at a first frequency have been positioned in a plane overlaying a plane containing microstrip antenna elements adapted for operation at a second frequency. Although such devices are capable of providing multiple frequency capabilities, they require relatively large surfaces or volumes, and are therefore disadvantageous when used in connection with portable devices. In addition, such arrangements can be expensive to manufacture, and can have undesirable interference and gain characteristics.

The amount of space required by an antenna is particularly apparent in connection with phased array antennas. Phased array antennas typically include a number of radiator elements arrayed in a plane. The elements can be provided with differentially delayed versions of a signal, to steer the beam of the antenna. The steering, or scanning, of an antenna's beam is useful in applications in which it is desirable to point the beam of the antenna in a particular direction, such as where a radio communications link is established between two points, or where information regarding the direction of a target object is desired. The elements comprising phased array antennas usually must be spread over a relatively large area. Furthermore, in order to provide phased array antennas

capable of operating at two different frequency bands, two separate arrays must be provided. Therefore, a conventional phased array antenna for operation at two different frequency bands can require twice the area of a single frequency band array antenna, and the phase centers of the separate arrays are not co-located. Alternatively, arrays can be stacked one on top of the other, however this approach results in antennas that are difficult to design such that they operate efficiently, and are expensive to manufacture. In addition, prior attempts at providing antenna arrays capable of operating at two distinct frequency bands have resulted in poor performance, including the creation of grating lobes, large amounts of coupling, large losses, and have required relatively large areas.

Therefore, there is a need for an antenna capable of operating at multiple frequencies that is relatively compact and that occupies a relatively small surface area. In addition, there is a need for such an antenna capable of providing a beam having high gain at multiple frequencies that can be scanned. Moreover, there is a need for an antenna capable of providing high gain at multiple frequencies that can be packaged within a relatively small area or volume, and that minimizes coupling and losses due to the close proximity of the antenna elements. Furthermore, it would be advantageous to provide an antenna capable of operating at multiple frequency bands and having co-located phase centers. In addition, such an antenna should be reliable and inexpensive to manufacture.

SUMMARY OF THE INVENTION

In accordance with the present invention, a dual band, coplanar, microstrip, interlaced array antenna is provided. The antenna includes a first plurality of antenna radiator elements forming a first array for operation at a first center frequency, interlaced

with a second plurality of antenna radiator elements forming a second array for operation at a second center frequency. The antenna is capable of providing high gain in both the first and second center frequencies. In addition, the antenna may be designed to provide a desired scan range for each of the operating frequency bands.

In accordance with an embodiment of the present invention, the first and second pluralities of antenna radiator elements are located within a common plane. In addition, radiator elements adapted for use in connection with the first operating frequency band may be interlaced with radiator elements adapted for operation at the second operating frequency band. Accordingly, the footprint or area of the first antenna array may substantially overlap with the footprint or area of the second antenna array. Therefore, a dual band array antenna may be provided within an area about equal to the area of a single band array antenna having comparable performance at one of the operating frequencies of the dual band antenna.

In accordance with an embodiment of the present invention, a dual band, coplanar, microstrip array antenna is formed using metallic radiator elements. Radiator elements for operation at a first operating frequency band of the antenna are provided in a first size, and overlay a substrate having a first dielectric constant. Radiator elements for operation in connection with the second operating frequency band of the antenna are provided in a second size, and are positioned over a substrate having a second dielectric constant. The radiator elements may be arranged in separate rectangular lattice formations to form first and second arrays. The elements of the first and second arrays are interlaced so that the

resulting dual band antenna occupies less area than the total area of the first and second arrays would occupy were their respective radiator elements not interlaced.

In accordance with still another embodiment of the present invention, a method for providing a dual frequency band antenna apparatus is provided. According to such a method, first and second center frequencies are selected. In addition, a scan range for the first center frequency and a scan range for the second center frequency are selected. From the wavelength corresponding to the first center frequency and the scan range for that first center frequency a lattice spacing for a first plurality of radiator elements is determined. The lattice spacing is the center to center spacing between radiator elements within an array of elements. Similarly, a lattice spacing for a second plurality of radiator elements is determined from the wavelength corresponding to the second center frequency and the scan range for the second center frequency. The maximum lattice spacing is the smaller of the lattice spacings for the first or second plurality of radiator elements. Where the scan range of one or both arrays is a first value in a first dimension and a second value in a second dimension, lattice spacing calculations may be made for each dimension.

A dielectric constant for a first substrate as a function of the wavelength of the first center frequency and the maximum lattice spacing may then be selected. The dielectric constant for the first substrate should have a value that is no less than 1.0. The dielectric constant for a second substrate may then be calculated as a function of the first substrate dielectric constant, the first center frequency, and the second center frequency. Next, an effective size of the radiator elements in the first plurality of radiator elements and of the radiator elements in the second plurality of radiator elements can be calculated

as a function of the wavelength of the operative center frequency and the corresponding dielectric constant of the substrate. A physical size of the first radiator elements and of the second radiator elements can then be calculated.

In accordance with a further embodiment of the present invention, a first plurality of radiator elements are formed on dielectric material having a dielectric constant equal to the first dielectric constant calculated according to the method. In addition, the second plurality of radiator elements is formed on dielectric material having a dielectric constant equal to the second dielectric constant. A first array may then be formed from the first plurality of radiator elements. The radiator elements of the first array are arranged about a rectangular lattice and have a center to center spacing equal to the calculated maximum lattice spacing. Similarly, a second array is formed from the second plurality of radiator elements. The radiator elements of the second array are arranged about a rectangular lattice and have a center to center spacing equal to the calculated maximum lattice spacing. The first array is then interlaced with the second array. Accordingly, a dual band antenna occupying a reduced surface area may be provided.

In accordance with another embodiment of the present invention, a method for modifying the effective dielectric constant of a material is provided. According to the method, portions of a material may be relieved, for example by forming holes in the material, in an area in which a modified (*i.e.* reduced) dielectric constant is desired. According to an embodiment of the present invention, a modified effective dielectric constant is obtained by forming holes in a triangular lattice pattern in an area of a dielectric material in which a reduced effective dielectric constant is desired. In

accordance with yet another embodiment of the present invention, a material having a modified effective dielectric constant is provided.

Based on the foregoing summary, a number of salient features of the present invention are readily discerned. A dual band antenna that allows for the scanning of the two center frequencies is provided. The antenna further allows for the provision of a dual band scanning antenna apparatus occupying a reduced surface area. The antenna allows support of both center frequencies with minimal or no grating lobes and minimal coupling. The antenna may be formed from two, co-planar, interlaced arrays. Furthermore, the present invention allows the provision of a dual band scanning antenna that occupies a reduced surface area, that provides a desired scan range of the operative frequencies and in which a desired amount of directivity is provided.

In addition, a material having a modified effective dielectric constant, and a method for modifying the effective dielectric constant of a material, are provided.

Additional advantages of the present invention will become readily apparent from the following discussion, particularly when taken together with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1A is a plan view of a dual band array antenna in accordance with an embodiment of the present invention;

Fig. 1B is a side elevation of the antenna of **Fig. 1A**;

Fig. 1C is a plan view of the back side of the antenna of **Fig. 1A**;

Fig. 2 is a side elevation of the radiator assembly of the antenna of **Figs. 1A-1C**;

Fig. 3 is a plan view of a dual band array antenna in accordance with another embodiment of the present invention;

Fig. 4 is a plan view of a dual band array antenna having dipole radiator elements in accordance with an embodiment of the present invention;

Fig. 5 is a plan view of a dual band array antenna having rectangular radiator elements in accordance with an embodiment of the present invention;

Fig. 6 is a plan view of a dual band array antenna having rectangular radiator elements in accordance with another embodiment of the present invention;

Fig. 7 is a plan view of a dual band array antenna having circular radiator elements in accordance with yet another embodiment of the present invention;

Fig. 8 is a flow chart illustrating a method of dimensioning a dual band array antenna in accordance with an embodiment of the present invention;

Fig. 9 is a flow chart illustrating the manufacture of a dual band array antenna in accordance with an embodiment of the present invention;

Figs. 10A-10D illustrate radiation patterns produced by a first array of a dual band array antenna operating at a first frequency in accordance with an embodiment of the present invention;

Figs. 11A-11D illustrate radiation patterns produced by a second array of a dual band array antenna operating at a second frequency in accordance with an embodiment of the present invention; and

Fig. 12 is a schematic representation of a dielectric material having a modified dielectric constant in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION

In accordance with the present invention, dual band array antennas and methods for providing dual band antennas are disclosed.

With reference now to **Fig. 1A**, a dual band array antenna **100** in accordance with an embodiment of the present invention is illustrated in plan view. In general, the antenna **100** comprises a first plurality of radiator elements **104** for operation at a first operating or center frequency f_1, and a second plurality of radiator elements **108** for operation at a second operating or center frequency f_2. The first plurality of radiator elements **104** are arranged about a rectangular lattice, with a center to center spacing equal to L_{max}, which is determined as will be described in greater detail below. Similarly, the second plurality of radiator elements **108** are arranged to form a second array arranged about a rectangular lattice in which the center to center spacing of the elements is also equal to L_{max}. The radiator elements **104, 108** may be formed on a substrate assembly **130**, as will be explained in greater detail below.

With reference now to **Fig. 1B**, the antenna system **100** of **Fig. 1A** is shown in a side elevation. As shown in **Fig. 1B**, the antenna system **100** may be considered as a radiator assembly **118**, generally comprising the substrate assembly **130** and the radiator elements **104, 108**, and a feed network **140**.

The feed network **140** is best illustrated in **Fig. 1C**, which depicts a side of the antenna system **100** opposite the side illustrated in **Fig. 1A**. In general, the feed network **140** comprises signal amplifiers and phase shifters, housed in enclosures **144**, and signal feed lines **148**. Certain of the feed lines **148** interconnect the radiator elements **104, 108**

to the amplifiers housed in the enclosures **144**. By positioning the amplifiers and phase shifters in close proximity to the radiator elements **104, 108**, the antenna system **100** illustrated in **Figs. 1A-1C** avoids the losses incurred from power divider circuits. Accordingly, the antenna system **100** illustrated in **Figs. 1A-1C** may be understood to be an active antenna system.

In addition, it should be appreciated that the feed lines **148** for passing signals between the radiator elements **104, 108** and corresponding amplifiers and phase shifters within the enclosures **144** may be interconnected to the radiator elements **104, 108** at one or a number of points. For example, as shown in **Fig. 1A**, feed lines **148** may be interconnected to radiator elements **104, 108** at two separate feed points **152**. In general, where the antenna system **100** is circularly polarized, the signal is provided from a single amplifier over a feed line **148**. A portion of that signal is then passed through a hybrid, such that the phase of the signal provided at a first feed point **152** is 90 degrees from the phase of the signal provided at the second feed point **156**. Furthermore, as can be appreciated by one of ordinary skill in the art, hybrids providing additional phase shifts may be used in connection with a greater number of feed points. For instance, when four feed points are provided on a radiator element, spaced 90 degrees apart about the element, hybrids capable of phase shifting the signal by 90, 180, and 270 degrees with respect to the signal provided to a first of the feed points may be used.

In accordance with yet another embodiment of the present invention, a dedicated amplifier is provided for supplying a properly phased signal to each feed point associated with a radiator element **104** or **108**. According to such an embodiment, an antenna

system **100**, such as the one illustrated in **Figs. 1A-1C** would include two amplifiers for each radiator element **104, 108**. Similarly, an antenna system utilizing more (*e.g.*, four) feed points would utilize a greater number (*e.g.*, four) amplifiers in connection with each radiator element **104, 108**. According to such an embodiment, the use of hybrids interposed between an amplifier and the radiator elements **104, 108** can be avoided. Such embodiments allow a large number of relatively small amplifiers to be used, and can increase the efficiency of the antenna system **100** as compared to systems in which hybrid circuits and/or power divider circuits are interposed between the amplifiers and the radiator elements **104, 108**.

As can be appreciated by one of ordinary skill in the art, the number of feed points that may be used in connection with a particular radiator element **104, 108** depends, at least in part, on the geometry of the radiator element **104, 108**. For instance, in connection with a circular radiator element **104, 108**, one, two or four feed points are typically used. Similarly, in connection with a square radiator element, one, two or four feed points may typically be used. Radiator elements having dipole configurations typically may use one or two feed points. The increased efficiency provided by the use of one or more amplifiers for each feed point is particularly advantageous in connection with applications involving the transmission of high-powered signals, or the reception of relatively small signals.

With reference now to **Fig. 2**, the radiator assembly **118** of **Figs. 1A-1C** is shown in detail in a side elevation. From **Fig. 2** it can be appreciated that the radiator elements **104** of the first array **112** are formed or mounted on a first dielectric material or substrate

120. The first dielectric material **120** has a first dielectric constant (e_{r1}), calculated as will be explained in detail below. Similarly, the radiator elements **108** of the second array **116** are formed or mounted on a second dielectric material or substrate **124** having a second dielectric constant (e_{r2}), calculated as will also be explained in detail below. The first **120** and second **124** dielectric materials may in turn be formed or attached to a conductive ground plane **128**. The first dielectric material **120**, the second dielectric material **124** and the ground plane **128** comprise the substrate assembly **130**. Furthermore, the radiator elements **104, 108** may be substantially coplanar in that they are interconnected to a common substrate assembly **130**. According to an embodiment of the present invention, the first plurality of radiator elements **104** may be situated in a first plane that is coplanar or substantially coplanar with a second plane in which the second plurality of radiator elements **108** are situated. For instance, the first dielectric material **120** associated with the first plurality of radiator elements **104** may be a first thickness, and the second dielectric material **124** associated with the second plurality of radiator elements **108** may be a second thickness, placing the first **104** and second **108** radiator elements in different planes. As a further example, the first and second planes may be within a distance equal to a thickness of at least one of the first **104** or second **108** radiator elements.

In accordance with an embodiment of the present invention, the radiator elements **104** and **108** comprise electrically conductive microstrip patches. The dielectric substrates **120** and **124** may be formed from any dielectric material having the required dielectric constant. For example, the second dielectric material **124** may be a DUROID material with a dielectric constant of 2.33 and the first dielectric material **120** may be a

DUROID material, modified as explained below, to have a dielectric constant of 1.5. In addition, one or both of the dielectric materials **120, 124** may be found from air, in which case the radiator elements **104** and/or **108** may be held in position over the ground plane by dielectric posts. The ground plane **128** may be any electrically conductive material. For example, the ground plane **128** may be metal. In general, any substrate assembly **130** configuration that provides a backing or a substrate for the first radiator elements **104** having a first dielectric constant (e_{r1}) and a backing or a substrate for the second radiator elements **108** having a second dielectric constant (e_{r2}) may be utilized in connection with the present invention. Furthermore, it should be appreciated that the first **120** and second **124** dielectric substrates may be formed from a common piece of material (*i.e.* the dielectric substrates **120, 124** may be integral to one another). According to such an embodiment, the dielectric constant in areas adjacent the first plurality of radiator elements **104** may be modified as compared to the dielectric constant in areas adjacent the second plurality of radiator elements **108**, or vice versa. In addition, it should be appreciated that a material may be modified to have a first dielectric constant (e_{r1}) value in areas adjacent the first plurality of radiator elements **104** and may be modified to have a second dielectric constant (e_{r2}) value in areas adjacent the second plurality of radiator elements **108**. The effective dielectric constant value of a material may be modified by using composite materials, or by forming holes in a dielectric material, as will be explained in detail below.

With continued reference to **Fig. 1**, the antenna **100** can be seen to comprise circular radiator elements **104** and **108**. In addition, it can be seen that each of the arrays **112** and **116** formed from the radiator elements **104** and **108** contains an equal number of radiator elements **104** or **108**. Of course, it is not necessary that the arrays **112** and **116** have an equal number of elements. Also with reference to **Fig. 1**, it can be appreciated that an overall area occupied by the first array **112**, denoted by dotted line **132** in **Fig. 1**, substantially overlaps with an overall area occupied by the second array **116**, denoted by dotted line **136** in **Fig. 1**. This overlap is achieved by interlacing the elements **104** of the first array **112** with the elements **108** of the second array **116**. Accordingly, an antenna **100** providing arrays **112** and **116** having different operating frequencies can be provided within an area that is substantially equal to an area of either the first array **112** or the second array **116** alone. Furthermore, the antenna **100** provides dual band capabilities in a relatively small surface area without the formation of undesirable grating lobes, and while providing a desired scan range and directivity.

As can be appreciated by one of ordinary skill in the art, the size of the arrays **112**, **116** (*i.e.* the area occupied by the arrays **112, 116**) is determined by the required beamwidth and the frequency of operation. In general, a narrow beam requires a larger array size and hence a larger number of elements. The converse is true for a broader beam. Also, for a given beamwidth, a physically larger array is required at a lower frequency than at a higher frequency. Furthermore, it can be appreciated that the arrays (or apertures) may be partially populated to realize the desired beamwidths at each of the operating frequencies.

With reference now to **Fig. 3**, a dual band antenna **300** in accordance with another embodiment of the present invention is illustrated. In general, the antenna **300** includes a first plurality of radiator elements **304** for operation at a first operating or center frequency f_1, and a second plurality of radiator elements **308** for operation at a second operating or center frequency f_2. As in the antenna system **100** shown in **Fig. 1**, the antenna **300** of **Fig. 3** comprises radiator elements **304** and **308** formed from circular patches. Also as in the antenna **100** of **Fig. 1**, the antenna **300** in **Fig. 3** features a first array **312** formed from the first plurality of radiator elements **304**, arranged about a rectangular lattice, and with a center to center spacing of the radiator elements **304** that is equal to L_{max}. The antenna **300** also includes a second array **316** formed from the second plurality of radiator elements **308**. The second array **316** includes elements spaced along a rectangular lattice and having a center to center spacing between elements **308** equal to L_{max}. The first and second arrays **312, 316** may be interconnected to one another by a substrate assembly **330** that provides a first dielectric constant adjacent the first radiator elements **304**, a second dielectric constant adjacent the second radiator elements **308**, and a common ground plane.

The first array **312** of the antenna **300** includes nine radiator elements **304** occupying a first area, denoted by dotted line **332** in **Fig. 3**. The second array **316** includes four radiator elements **308** occupying a second area, denoted by dotted line **336**. As can be appreciated from **Fig. 3**, the elements **304** of the first array are interlaced with the elements **308** of the second array **316**, such that the area **336** occupied by the second array **316** substantially overlaps with the area **332** occupied by the first array **312**.

Furthermore, it can be appreciated that the areas **332**, **336** of the first **312** and the second **316** arrays are centered about the same point.

In **Fig. 4**, a dual band antenna **400** in accordance with still another embodiment of the present invention is illustrated. In general, the antenna **400** includes a first plurality of radiator elements **404** for operation at a first operating or center frequency f_1, and a second plurality of radiator elements **408** for operation at a second operating or center frequency f_2. In the antenna **400** depicted in **Fig. 4**, a first array **412** is formed from the first plurality of radiator elements **404**. The radiator elements **404** of the first array **412** are arranged about a rectangular lattice and have a center to center spacing equal to L_{max}. A second array **416** is formed from the second plurality of radiator elements **408**. The radiator elements **408** of the second array **416** are arranged about a rectangular lattice, and have a center to center spacing that is also equal to L_{max}. The radiator elements **404**, **408** in the embodiment shown in **Fig. 4** have a dipole configuration. Therefore, it can be appreciated that various radiator configurations may be used in connection with the present invention.

The first array **412** of the antenna **400** includes nine radiator elements **404** occupying a first area, denoted by dotted line **420** in **Fig. 4**. The second array **416** includes four radiator elements **408** occupying a second area, denoted by dotted line **424**. As can be appreciated from **Fig. 4**, the elements **404** of the first array **412** are interlaced with the elements **408** of the second array **416**, such that all of the area **424** occupied by the second array **416** is included in the area **420** occupied by the first array **412**. Therefore, it can be appreciated that the first **412** and second **416** arrays occupy areas **420**,

424 that substantially overlap. This overlap of the first **412** and second **416** arrays substantially decreases the surface area required by an antenna having the operating characteristics of the antenna **400**.

The radiator elements **404, 408** may be located in common plane, formed on a substrate assembly **430** that provides a first dielectric constant with respect to the first radiator elements **404**, a second dielectric constant with respect to the second radiator elements **408**, and a common ground plane. In addition to the relatively small surface area required by the dual band antenna **400**, it will be noted that the areas **420, 424** occupied by the arrays **412, 416** share a common center point. Accordingly, the arrays **412, 416** of the antenna **400** provide co-located phase centers.

With reference now to **Fig. 5**, a dual band antenna **500** in accordance with still another embodiment of the present invention is illustrated. In general, the antenna **500** includes a first plurality of radiator elements **504**, forming a first array **508** for operating at a first operating or center frequency f_1. In addition, a second plurality of radiator elements **512** are provided, forming a second array **516** for operating at a second operating or center frequency f_2. Each of the elements **504, 512** of the first **508** and second **516** arrays are arranged about rectangular lattices and have a center to center spacing with respect to other elements of their respective array equal to L_{max}.

The elements **504, 512** of the dual band antenna **500** illustrated in **Fig. 5** are square in outline. In addition, the sides of the radiator elements **504, 512** are angled with respect to the sides of the rectangular lattice about which the radiator elements **504, 512** are positioned. The first array **508** is formed from nine radiator elements **504** occupying a

first area denoted by dotted line **520**. The second array **516** includes four radiator elements **512** occupying a second area denoted by dotted line **524**. From **Fig. 5**, it can be appreciated that the first area **520** includes all of the second area of **524**. Furthermore, it can be appreciated that the second array **516** is centered with respect to the first array **508**. Accordingly, the first **508** and second **516** arrays of the antenna **500** have co-located phase centers. The first **508** and **516** arrays may be formed on a substrate assembly **530** that provides a first dielectic constant with respect to the first plurality of radiator elements **508**, a second dielectric constant with respect to the second plurality of radiator elements **512**, and a common ground plane.

In **Fig. 6**, a dual band antenna **600** in accordance with still another embodiment of the present invention is illustrated. In general, the antenna **600** includes a first plurality of square radiator elements **604**, forming a first array **608** for operation at a first operating or center frequency f_1. The antenna **600** additionally includes a second plurality of square radiator elements **612** forming a second array **616** for operation at a second operating or center frequency f_2. The radiator elements **604** of the first array **608** are arranged about a rectangular lattice and are spaced from one another by a distance equal to L_{max}. Similarly, the second radiator elements **612** are spaced about a rectangular lattice and have a center to center distance from one another that is also equal to L_{max}. The elements **604** of the first array **608** are interlaced with the elements **612** of the second array **616** to minimize the surface area occupied by the antenna **600**. In particular, in **Fig. 6** it is apparent that the area occupied by the first array **608**, denoted by dotted line **620**, is essentially the same as the area occupied by the second array **616**, denoted by dotted line **624**.

Furthermore, it can appreciated that the areas **620**, **624** share a common center point, allowing the first **608** and second **616** arrays to share a common phase center. The arrays **608, 616** may be formed on a common substrate assembly **630** providing appropriate dielectric constants, over a common ground plane.

With reference now to **Fig.** 7, a dual band antenna **700** in accordance with still another embodiment of the present invention is illustrated. In general, the dual band antenna **700** comprises a first plurality of radiator elements **704** forming a first array **708** for operation at a first operating or center frequency f_1. In addition, the antenna **700** comprises a second plurality of radiator elements **712** forming a second array **716** for operation at a second operating or center frequency f_2. As in the embodiments illustrated in **Figs. 1** and **3**, the radiator elements **704**, **712** of the dual band antenna **700** are circular. The radiator elements **704** of the first array **708** are arranged about a rectangular lattice and have a center to center spacing equal to L_{max}. Similarly, the radiator elements **712** of the second array **716** are arranged about a rectangular lattice and have a center to center spacing equal to L_{max}.

In the embodiment illustrated in **Fig.** 7, each of the arrays **708, 716** comprises 64 radiator elements **704, 712.** The radiator elements **704** comprising the first array **708** generally occupy an area denoted by dotted line **720**. The radiator elements **712** comprising the second array **716** generally occupy a second area denoted by dotted line **724**. The first **720** and second **724** areas substantially overlap. The arrays **708, 716** may be formed on a substrate assembly **730** that provides a first dielectric constant (e_{r1}) with respect to the radiator elements **704** of the first array **708**, a second dielectric constant (e_{r2})

with respect to the radiator elements **712** of the second array **716**, and a common ground plane.

With reference now to **Fig. 8**, a flow chart illustrating a method of dimensioning a dual band array antenna in accordance with an embodiment of the present invention is shown. Initially, at step **800**, the first (f_1) and second (f_2) center or operating frequencies of the dual band antenna are selected. In general, the first and second center frequencies will be determined by the system in connection with which the antenna is to be used. For example, in a global positioning system (GPS) application, an antenna for use on a GPS satellite may have a first center frequency of 1,575 Megahertz and a second center frequency of 1,227 Megahertz. Next, a scan range for each of the center frequencies is selected (step **804**). Continuing the example of a GPS satellite application, the first and second center frequencies may both have a scan range of 14°.

From the selected frequency and scan range parameters, a maximum lattice spacing for the first and second arrays that will comprise the dual band antenna are calculated (step **808**). In particular, the maximum lattice spacing for the first array (L_1) is given by $L_1 < \lambda_1/(1 + \sin(\theta_1))$, where λ_1 is the wavelength of the carrier signal at the first center frequency, and where θ_1 is the scan range for the signal at the first center frequency. Similarly, the maximum lattice spacing for the second array (L_2) is given by $L_2 < \lambda_2/(1 + \sin(\theta_2))$, where λ_2 is the wavelength of the carrier signal at the second center frequency, and where θ_2 is the scan range for the signal at the second center frequency. The maximum lattice spacing (L_{max}) is the largest spacing value that satisfies both the requirements for L_1 and the requirements for L_2. (Step **812**).

A minimum dielectric constant value (e_{r1}) for a first substrate adjacent the radiator elements of the first array is then selected. The value for e_{r1} is given by the following: $e_{r1} > 0.8453\ (\lambda_1/L_{max})^2$, where e_{r1} is also no less than 1.0. (Step **816**). Once the minimum dielectric constant value for the first array has been calculated, the dielectric constant value (e_{r2}) for a second substrate adjacent the radiator elements of the second array can be calculated from the equation $e_{r2} = e_{r1} *(f_1/f_2)^2$ (Step **820**). Next, the effective diameter (D) of the radiator elements can be calculated from the equation $Dneff = \left(\frac{0.65\lambda_n}{\sqrt{e_{rn}}}\right)$ (Step **824**).

Then, the actual diameters of the radiator elements may be calculated using conventional methods (step **828**). A check may then be made to ensure that the effective diameters of the interlaced radiator elements will not encroach on one another at the selected lattice spacing L_{MAX} (i.e. that $D_{1eff} + D_{2eff} < 1.414*L$ for a square lattice) (Step **832**). If the effective diameters of adjacent radiator elements do encroach on one another, a greater dielectric constant value (e_{r1}) for the first substrate may be selected, and a new dielectric constant value (e_{r2}) for the second substrate may be calculated. The effective diameters of the radiator elements may then be recalculated, and a check may again be made to ensure that the effective diameters of the radiator elements do not encroach on one another.

As can be appreciated by one of ordinary skill in the art, a phased array antenna may be scanned in two dimensions. For antennas in which the scan range for both arrays is the same in both dimensions, the value obtained for L_{max} is also the same in both dimensions. Furthermore, it can be appreciated that the rectangular lattice spacing

obtained for the radiator elements results in a square lattice when the scan ranges in two dimensions are the same.

If different scan ranges are desired for the two dimensions, separate calculations are made for the element spacing in each of the two dimensions. That is a maximum element spacing for the first array in the x dimension L_{1x}, a maximum element spacing for the first array in the y dimension L_{1y}, a maximum element spacing for the second array in the x dimension L_{2x}, and a maximum element spacing for the second array in y dimension L_{2y} are calculated. The smaller of the L_{1x} and L_{2x} is then selected as L_{maxx} (*i.e.* the maximum lattice spacing the x dimension), and the smaller of L_{1y} and L_{2y} is selected as L_{maxy} (*i.e.* the maximum lattice spacing in y dimension). As can be appreciated, an antenna in accordance with the present invention having different scan ranges in two dimensions may therefore have a rectangular lattice spacing that is not square.

As can also be appreciated, the scan ranges for the first and second array need not be equal. Therefore, as many as four different scan ranges may be associated with an antenna in accordance with the present invention.

Where different lattice spacings are used for the x and y dimensions, a different check must be made to ensure that the effective diameters of the interlaced radiator elements will not encroach on one another. In particular, the inequality

$D_{1eff} + D_{2eff} < \sqrt{L_1^2 + L_2^2}$ must be satisfied.

The method disclosed herein for dimensioning a dual band array antenna allows radiator elements of the first and second arrays to be interlaced with one another to

minimize the surface area occupied by the antenna. In addition, the disclosed method provides a dual band antenna with interlaced arrays with minimal or no grating lobes or losses, such as can occur when large distances separate radiator elements of an array. The disclosed method for dimensioning a dual band antenna also results in minimal coupling and losses at the operating frequencies that might otherwise be caused by the close proximity of the radiator elements of the two arrays. Furthermore, the electrical spacing between the radiator elements is optimized by providing proper dielectric loading of the radiator elements.

With reference now to **Fig. 9**, a flow chart illustrating the manufacture of a dual band array antenna in accordance with an embodiment of the present invention is illustrated. Initially, at step **900**, the dual band co-planar antenna is dimensioned as described above in connection with **Fig. 8**. Next, a first plurality of antenna elements is formed on a first dielectric (step **904**). A second plurality of antenna elements is then formed on a second dielectric material **908**. At step **912**, the first plurality of antenna elements is positioned on a ground plane in a rectangular lattice pattern, with a lattice spacing equal to L_{max} to form a first array. At step **916**, the second plurality of antenna elements is positioned on the ground plane in a rectangular lattice pattern with a lattice spacing equal to L_{max} to form a second array interlaced with the first array.

As an example of the dimensioning of a phased array antenna in accordance with an embodiment of the invention, the selected first center or operating frequency (f_1) may be equal to 1,575 megahertz, and the second operating or center frequency (f_2) may be equal to 1,227 megahertz. The selected scan ranges for both frequencies may be 14 degrees. Initially, L_{MAX} is calculated from $L_n < \lambda_n/(1 + \sin(\theta_n))$ to equal 15.337 cm. Next,

a first dielectric constant value (e_{r1}) that satisfies the inequality $e_{r1} > 0.8453 (\lambda_1/L_{max})^2$ and that is no less than 1.0 is chosen. According to the present example, a value of e_{r1} = 1.3038 is selected. Next, a second dielectric constant value (e_{r2}) is calculated as follows: $e_{r2} = e_{r1}(f_1/f_2)^2 = 2.1482$. The effective diameter D_{neff} is then calculated from

$Dneff = \left(\frac{0.65\lambda_n}{\sqrt{e_{rn}}}\right)$ j to be 10.843 cm. Finally, using circular radiator elements, the radiator elements of the first array are calculated to have a diameter of 8.7 cm, and the radiator elements of the second array are calculated to have a diameter of 9.2 cm. According to this example, both arrays have an equal scan range in each dimension. Therefore, only one value for L_{max} is calculated, and the elements of the arrays are arranged about a square lattice.

In **Figs. 10A-10D**, the radiation pattern produced by a first array of antenna elements included as part of an example dual band array antenna in accordance with the present invention in various planes (ϕ = 0, 45, 90 and 135 degrees) through the antenna and for a first operating frequency are illustrated. In **Figs. 11A-11D**, the radiation patterns produced by a second array of antenna elements included as part of the example dual band frequency antenna in various planes (ϕ = 0, 45, 90 and 135 degrees) through the antenna and for a second operating frequency are illustrated. The radiation patterns illustrated in **Figs. 10** and **11** are practically indistinguishable from the radiator patterns obtained from independent, non-interlaced arrays that provide similar operating characteristics. Therefore, it can be appreciated that the present invention provides dual

band antenna characteristics using an antenna that occupies much less area than a conventional antenna utilizing two independent, non-interlaced arrays capable of providing comparable operating characteristics.

As can be appreciated by one of ordinary skill in the art, materials having certain dielectric constants may not be available, or may be difficult and expensive to obtain. In accordance with an embodiment of the present invention, the dielectric constant of a solid sheet of material **1200** may be lowered by drilling holes **1204** of appropriate diameter in a uniform, equilateral triangular pattern, as shown in **Fig. 12**. Using an equivalent static capacitance approach, the modified effective dielectric constant e_m is given by the equation $e_m = e_r - 0.25(e_r - 1)\pi d^2/0.866S^2$, where e_r is the dielectric constant of the solid material, S is the nearest neighbor spacing between the holes, and d is the diameter of the holes.

In general, when using this technique, S and d should be very small compared to the highest operating wavelength of the radiator elements used in connection with the dielectric material. For example, the inventors have found that acceptable results are obtained if S and d are both less than $\lambda/64$, where λ is equal to the wavelength of the highest operating frequency of the antenna. In addition, S must be greater than d, since S - d represents the wall thickness between holes. Accordingly, in order to use this method, one starts with a hole diameter d that is less than $\lambda/64$, and then calculates the spacing S using the following equation, which can be readily derived from the equation given above for the modified dielectric constant:

$$S = 0.9523\, d \sqrt{\frac{(e_r - 1)}{(e_r - e_m)}}\ .$$

If the resulting wall thickness S - d is too small or is negative, the dielectric constant of the solid material cannot be lowered to the desired level without violating the condition that d be less than $\lambda/64$ using this approach.

As an example, the dielectric constant value e_r of a typical substrate material is 2.33. According to the present example, it will be assumed that the desired modified effective dielectric constant e_m is 1.5. The diameter of the holes will be selected to be d = 0.0635 inch, which corresponds to a standard drill bit size, and which satisfies the inequality $d < \lambda/64$. Using the equation given above, we obtain a value of S = 0.0764 inch. This corresponds to a wall thickness of 0.0129 inch.

If a lower modified effective dielectric constant were desired, for example, $e_m = 1.4$, then a larger hole diameter, for example, 0.1 inch, could be used. According to this second example, S is equal to 0.1137, resulting in a wall thickness of 0.0137 inch. Using this configuration, S and d would continue to satisfy the requirement that they be less than $\lambda/64$ up to a frequency of 1,623 MHZ. Therefore, such a configuration could be used in connection with GPS frequencies, which are 1,227 MHZ and 1,575 MHZ. Furthermore, it should be noted that the requirement that S and d be less than $\lambda/64$ is a guideline, and can be exceeded in particular circumstances.

The disclosed technique for modifying the dielectric constant of a solid sheet of material is particularly suited for use in connection with dual frequency arrays with

interleaved elements as described herein. The hole patterns in the dielectric substrates can be locally tailored to provide the desired dielectric constant required by the radiating elements operating at each frequency. Therefore, in accordance with the present invention, it can be appreciated that the first **120** and second **124** dielectric materials may be formed from a common dielectric material, with the effective dielectric constant of the material modified with respect to either or both of the first and/or second pluralities of radiator elements **104, 108**. In addition, it should be appreciated that the dielectric materials **120, 124** can be formed from a single sheet or piece of dielectric material that is modified in areas adjacent to the first plurality of radiator elements **104** using a first diameter and spacing of holes, and is modified in areas adjacent the second plurality of radiator elements **108** using a second diameter and spacing between holes.

The foregoing discussion of the invention has been presented for purposes of illustration and description. Further, the description is not intended to limit the invention to the form disclosed herein. Consequently, variations and modifications commensurate with the above teachings, within the skill and knowledge of the relevant art, are within the scope of the present invention. The embodiments described hereinabove are further intended to explain the best mode presently known of practicing the invention, and to enable others skilled in the art to utilize the invention in such and in other embodiments and with various modifications required by their particular application or use of the invention. It is intended that the appended claims be construed to include alternative embodiments to the extent permitted by the prior art.